On Continuum-State and Bound-State β^-–Decay Rates of the Neutron

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We analyse the continuum-state and bound-state β^-–decay rates of the neutron. For the calculation of theoretical values of the decay rates we use the new value for the axial coupling constant $g_A = 1.2750(9)$, obtained recently by H. Abele (Progr. Part. Nucl. Phys., **60**, 1 (2008)) from the fit of the experimental data on the neutron spin-electron correlation coefficient of the electron energy spectrum of the continuum-state β^-–decay of the neutron. We take into account the contribution of radiative corrections and the scalar and tensor weak couplings. We define correlation coefficients of the electron energy spectrum in terms of axial, scalar and tensor coupling constants. Using recent precise experimental data for the lifetime of the neutron and correlation coefficients we estimate the scalar and tensor weak coupling constants. The bound-state β^-–decay rates of the neutron we calculate as functions of axial, scalar and tensor weak coupling constants. We show that dominantly the neutron decays into hydrogen in the hyperfine states with total angular momentum $F = 0$. The calculated angular distributions of the probabilities of the bound-state β^-–decays of the polarised neutron can be used for the experimental measurements of the bound-state β^-–decays into the hyperfine states with a total angular momentum $F = 1$.

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INTRODUCTION

The continuum-state β^-–decay of the neutron $n \to p + e^- + \tilde{\nu}_e$ is experimentally well measured [1, 2] (see also [3] and [4]) and investigated theoretically [5, 8]. A theoretical analysis of the bound-state β^-–decay rate has been carried out in [9, 10]. Recently [11, 12] Schott *et al.* have reported new experimental data on the bound-state β^-–decay of the neutron $n \to \mathrm{H} + \tilde{\nu}_e$.

In this paper we recalculate the continuum-state β^-–decay rate of the neutron, the electron energy spectrum and angular distribution taking into account the contributions of $V-A$, scalar S and tensor T weak interactions and radiative corrections [13, 14]. Such a recalculation is required by the new precise experimental data on the lifetime of the neutron $\tau_{\beta^-_c} = 878.5(8)\,\mathrm{s}$ [1] and the value of the axial coupling constant $g_A = 1.2750(9)$ [3]. Using recent experimental data on the lifetime of the neutron [1] and correlation coefficients [3] we estimate the scalar g_S and tensor g_T coupling constants. For the experimental analysis of the contributions of the scalar and tensor weak interactions we give angular distributions of the probabilities of the bound-state β^-–decay rates of the polarised neutron. The calculation of the bound-state β^-–decay rates we use the technique applied to the analysis of the weak decays of the H–like, He–like and bare heavy ions and mesic hydrogen in [15]–[17]. In the Conclusion we discuss the obtained results. In the Appendix we discuss the radiative corrections.

$V-A$ WEAK HADRONIC INTERACTIONS

The Hamiltonian of weak interaction we take in the form [15]–[17]

$$\mathcal{H}_W(x) = \frac{G_F}{\sqrt{2}}\,V_{ud}\,[\bar{\psi}_p(x)\gamma_\mu(1 - g_A\gamma^5)\psi_n(x)] \times [\bar{\psi}_e(x)\gamma^\mu(1-\gamma^5)\psi_{\nu_e}(x)], \qquad (1)$$

where $G_F = 1.1664\times 10^{-11}\,\mathrm{MeV}^{-2}$ is the Fermi weak constant, V_{ud} and g_A are the CKM matrix element and the axial coupling constant [4], $\psi_p(x)$, $\psi_n(x)$, $\psi_e(x)$ and $\psi_{\nu_e}(x)$ are operators of interacting proton, neutron, electron and anti-neutrino, respectively.

For numerical calculations we will use the most precise values $|V_{ud}| = 0.97419(22)$ [4] and $g_A = 1.2750(9)$ [3], where $g_A = 1.2750(9)$ has been obtained from the fit of the neutron spin–electron correlation coefficient $A^{\exp} = -0.11933(34)$, defined in terms of the axial coupling g_A in Eq.(32), of the electron energy spectrum for the continuum-state β^-–decay of the neutron [3].

The value of the CKM matrix element $|V_{ud}| = 0.97419(22)$ [4] agrees well with $|V_{ud}| = 0.9738(4)$ [3, 19], measured from the superallowed $0^+ \to 0^+$ nuclear β^-–decays, which are pure Fermi transitions [19]. It satisfies also well the unitarity condition $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.0000(6)$ for the CKM matrix elements [4].

The $\mathbb{T}$–matrix of weak interactions is equal to

$$\mathbb{T} = -\int d^4x\, \mathcal{H}_W(x). \tag{2}$$

The amplitudes of the continuum-state and bound-state β^-–decays of the neutron are defined by the matrix elements of the $\mathbb{T}$–matrix

$$\begin{aligned}\langle \tilde{\nu}_e e^- p|\mathbb{T}|n\rangle &= (2\pi)^4\delta^{(4)}(k_{\tilde{\nu}_e} + k_e + k_p - k_n)\\ &\quad\times M(n \to p + e^- + \tilde{\nu}_e),\\ \langle \tilde{\nu}_e H|\mathbb{T}|n\rangle &= (2\pi)^4\delta^{(4)}(k_{\tilde{\nu}_e} + k_{\mathrm{H}} - k_n)\\ &\quad\times M(n \to k_H + \tilde{\nu}_e).\end{aligned} \tag{3}$$

The amplitudes $M(n \to p + e^- + \tilde{\nu}_e)$ and $M(n \to k_H + \tilde{\nu}_e)$ of the decays are

$$\begin{aligned}M(n \to p + e^- + \tilde{\nu}_e) &= -\langle \tilde{\nu}_e e^- p|\mathcal{H}_W(0)|n\rangle,\\ M(n \to k_H + \tilde{\nu}_e) &= -\langle \tilde{\nu}_e \mathrm{H}|\mathcal{H}_W(0)|n\rangle,\end{aligned} \tag{4}$$

where k_a with $a = \tilde{\nu}_e, e, p, \mathrm{H}$ and n are the 4–momenta of interacting particles.

BOUND-STATE AND CONTINUUM-STATE β^-–DECAY RATES OF NEUTRON IN $V-A$ THEORY OF WEAK INTERACTIONS

In the final state of the bound-state β^-–decay of the neutron hydrogen can be produced only in the ns–states, where n is a *principal* quantum number $n = 1, 2, \ldots$ [16, 17]. The contribution of the excited $n\ell$-state with $\ell > 0$ is negligibly small. Due to hyperfine interactions [20, 21] hydrogen can be in two hyperfine states $(ns)_F$ with $F = 0$ and $F = 1$

The wave function of hydrogen H in the ns–state we take in the form [22]–[24]

$$\begin{aligned}&|\mathrm{H}^{(ns)}(\vec{q}\,)\rangle = \frac{1}{(2\pi)^3}\sqrt{2E_{\mathrm{H}}(\vec{q}\,)}\\ &\times\int \frac{d^3k_e}{\sqrt{2E_e(\vec{k}_e)}}\frac{d^3k_p}{\sqrt{2E_p(\vec{k}_p)}}\,\delta^{(3)}(\vec{q} - \vec{k}_e - \vec{k}_p)\\ &\times\phi_{ns}\Big(\frac{m_p\vec{k}_e - m_e\vec{k}_p}{m_p + m_e}\Big)a^\dagger_{ns}(\vec{k}_e, \sigma_e)a^\dagger_p(\vec{k}_p, \sigma_p)|0\rangle,\end{aligned} \tag{5}$$

where $E_{\mathrm{H}}(\vec{q}\,) = \sqrt{M^2_{\mathrm{H}} + \vec{q}^{\,2}}$ and $\vec{q}$ are the total energy and the momentum of hydrogen, $M_{\mathrm{H}} = m_p + m_e + \epsilon_{ns}$ and ϵ_{ns} are the mass and the binding energy of hydrogen H in the $(ns)_F$ hyperfine state; $\phi_{ns}(\vec{k}\,)$ is the wave function of the ns–state in the momentum representation [20] (see also [22]–[24]). For the calculation of the bound state β^-–decay rate we can neglect the hyperfine splitting of the energy levels of the ns–states [20, 21].

For the amplitude of the bound-state β^-–decay we obtain the following expression

$$\begin{aligned}&M(n \to \mathrm{H}^{(ns)} + \tilde{\nu}_e) = G_F V_{ud}\sqrt{2m_n 2E_{\mathrm{H}} 2E_{\tilde{\nu}_e}}\\ &\times\int \frac{d^3k}{(2\pi)^3}\,\phi^*_{ns}\Big(\vec{k} - \frac{m_e}{m_p + m_e}\,\vec{q}\Big)\Big\{[\varphi^\dagger_e\chi_{\tilde{\nu}_e}]\\ &\times[\varphi^\dagger_p\varphi_n] - g_A\,[\varphi^\dagger_e\vec{\sigma}\,\chi_{\tilde{\nu}_e}]\cdot[\varphi^\dagger_p\vec{\sigma}\,\varphi_n]\Big\},\end{aligned} \tag{6}$$

where φ_p, φ_n, φ_e and $\chi_{\tilde{\nu}_e}$ are spinorial wave functions of the proton, neutron, electron and antineutrino. The integral over $\vec{k}$ of the wave function $\phi^*_{ns}(\vec{k}\,)$ defines the wave function $\psi^*_{ns}(0)$ in the coordinate representation, equal to $\psi^*_{ns}(0) = \sqrt{\alpha^3 m^3_e/n^3\pi}$, where m_e is the electron mass and $\alpha = 1/137.036$ is the fine–structure constant. This gives

$$\begin{aligned}&M(n \to \mathrm{H}^{(ns)} + \tilde{\nu}_e) = G_F V_{ud}\sqrt{2m_n 2E_{\mathrm{H}} 2E_{\tilde{\nu}_e}}\\ &\times\Big\{[\varphi^\dagger_e\chi_{\tilde{\nu}_e}][\varphi^\dagger_p\varphi_n] - g_A[\varphi^\dagger_e\vec{\sigma}\,\chi_{\tilde{\nu}_e}]\cdot[\varphi^\dagger_p\vec{\sigma}\,\varphi_n]\Big\}\\ &\times\psi^*_{(ns)_F}(0).\end{aligned} \tag{7}$$

The bound-state β^-–decay rate of the neutron is

$$\begin{aligned}&\lambda_{\beta^-_b} = \frac{1}{2m_n}\int\frac{1}{2}\sum^{\infty}_{n=1}\sum_{\sigma_n,\sigma_p,\sigma_e}|M(n \to \mathrm{H}^{(ns)} + \tilde{\nu}_e)|^2\\ &\times(2\pi)^4\delta^{(4)}(k_{\tilde{\nu}_e} + q - p)\,\frac{d^3q}{(2\pi)^3 2E_{\mathrm{H}}}\frac{d^3k_{\tilde{\nu}_e}}{(2\pi)^3 2E_{\tilde{\nu}_e}}.\end{aligned} \tag{8}$$

Summing over the *principal* quantum number and polarisations we get

$$\begin{aligned}\lambda_{\beta^-_b} &= (1 + 3g^2_A)\,\zeta(3)\,G^2_F|V_{ud}|^2\frac{\alpha^3 m^3_e}{\pi^2}\\ &\times\sqrt{(m_p + m_e)^2 + Q^2_{\beta^-_c}}\,\frac{Q^2_{\beta^-_c}}{m_n},\end{aligned} \tag{9}$$

where $\zeta(3) = 1.202$ is the Riemann function, coming from the summation over the *principal* quantum number n, and $Q_{\beta^-_c}$ is the Q–value of the continuum-state β^-–decay of the neutron equal to

$$Q_{\beta^-_c} = \frac{m^2_n - (m_p + m_e)^2}{2m_n} = 0.782\,\mathrm{MeV}. \tag{10}$$

In the literature [9, 10] the bound-state β^-–decay rate of the neutron is defined relative to the continuum-state β^-–decay rate of the neutron.

The theoretical value of the continuum-state β^-–decay rate of the neutron is

$$\begin{aligned}\lambda_{\beta^-_c} &= (1 + 3g^2_A)\,\frac{G^2_F|V_{ud}|^2}{2\pi^3}\,f(Q_{\beta^-_c}, Z = 1) =\\ &= 1.0931(14)\times 10^{-3}\,\mathrm{s}^{-1},\end{aligned} \tag{11}$$

where the error of the decay rate is fully defined by the experimental error of the axial coupling constant $g_A = 1.2750(9)$ and the CKM matrix element $|V_{ud}| = 0.97419(22)$. The numerical value of the continuum-state β^-–decay rate of the neutron is calculated for the experimental masses of the interacting particles [4] and the Fermi integral $f(Q_{\beta^-_c}, Z = 1)$ equal to

$$
\begin{aligned}
f(Q_{\beta^-_c}, Z = 1) &= \int^{Q_{\beta^-_c}+m_e}_{m_e} (Q_{\beta^-_c} + m_e - E_e)^2 \\
&\times E_e\sqrt{E^2_e - m^2_e}\, F(E_e, Z = 1)\, dE_e = \\
&= \int^{Q_{\beta^-_c}+m_e}_{m_e} \frac{2\pi\alpha E^2_e (Q_{\beta^-_c} + m_e - E_e)^2}{1 - e^{-\,2\pi\alpha E_e/\sqrt{E^2_e - m^2_e}}}\, dE_e = \\
&= 0.0588\,\mathrm{MeV}^5
\end{aligned}
\qquad (12)
$$

and the Fermi function [7]

$$
\begin{aligned}
&F(E_e, Z = 1) = \\
&= \frac{2\pi\alpha E_e}{\sqrt{E^2_e - m^2_e}}\, \frac{1}{1 - e^{-\,2\pi\alpha E_e/\sqrt{E^2_e - m^2_e}}}.
\end{aligned}
\qquad (13)
$$

The theoretical value of the lifetime of the neutron is $\tau_{\beta^-_c} = 914.8(1.2)\,\mathrm{s}$, defined by $\tau_{\beta^-_c} = 1/\lambda_{\beta^-_c}$.

Taking into account the radiative corrections [13, 14] (see the Appendix), the theoretical value of the lifetime reduces to $\tau^{(\gamma)}_{\beta^-_c} = 880.4.(1.1)\,\mathrm{s}$. It agrees well with the experimental $\tau^{\rm exp}_{\beta^-_c} = 878.5(8)\,\mathrm{s}$ [1]. The theoretical value of the lifetime $\tau^{(\gamma)}_{\beta^-_c} = 880.4(1.1)\,\mathrm{s}$ differs from the world averaged experimental value $\tau^{\rm exp}_{\beta^-_c} = 885.7(8)\,\mathrm{s}$ [4] by a few seconds $(-\,5.3 \pm 1.4)\,\mathrm{s}$.

For the ratio $R_{b/c} = \lambda_{\beta^-_b}/\lambda^{(\gamma)}_{\beta^-_c}$ of the bound-state and continuum-state β^-–decay rates of the neutron we get the following expression

$$
\begin{aligned}
R_{b/c} &= \zeta(3) 2\pi \frac{\alpha^3 m^3_e Q^2_{\beta^-_c}}{m_n} \frac{\sqrt{(m_p + m_e)^2 + Q^2_{\beta^-_c}}}{f^{(\gamma)}(Q_{\beta^-_c}, Z = 1)} = \\
&= 3.92 \times 10^{-6},
\end{aligned}
\qquad (14)
$$

where the Fermi integral $f^{(\gamma)}(Q_{\beta^-_c}, Z = 1) = 0.0611\,\mathrm{MeV}^5$ is calculated in the Appendix Eq.(A-1). Our value for the ratio of the decay rates agrees with the results obtained in [9] (see also [11, 12]): $R_{b/c} = 4.20 \times 10^{-6}$.

In spite of such a success of the $V - A$ theory of weak interactions for the description of the continuum-state β^-–decay rate of the neutron, in the next section we take into account the contributions of scalar S and tensor T weak interactions of baryons and leptons and estimate the values of the scalar and tensor coupling constants [5, 8].

CONTINUUM-STATE AND BOUND-STATE β^-–DECAY RATES OF NEUTRON IN $V - A$, SCALAR AND TENSOR THEORY OF WEAK INTERACTIONS

In this section we consider the continuum-state and bound-state β^-–decays of the neutron by taking into account scalar and tensor weak interactions [5, 8]. The effective low–energy Hamiltonian of these interactions can be taken in the following form

$$
\begin{aligned}
\tilde{\mathcal{H}}_W(x) &= \frac{G_F}{\sqrt{2}}\, V_{ud} \Big\{ g_S\, [\bar{\psi}_p(x)\psi_n(x)] \\
&\times [\bar{\psi}_e(x)(1 - \gamma^5)\psi_{\nu_e}(x)] + \frac{1}{2}\, g_T\, [\bar{\psi}_p(x)\sigma_{\mu\nu}\gamma^5\psi_n(x)] \\
&[\bar{\psi}_e(x)\sigma^{\mu\nu}(1 - \gamma^5)\psi_{\nu_e}(x)]\Big\},
\end{aligned}
\qquad (15)
$$

where g_S and g_T are constants of scalar and tensor weak interactions and $\sigma_{\mu\nu} = \frac{1}{2}(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)$ is the Dirac matrix.

In the non–relativistic approximation for the neutron and the proton the contribution of the scalar and tensor weak interactions to the amplitude of the continuum-state β^-–decay is

$$
\begin{aligned}
\tilde{M}(n \to p + e^- + \tilde{\nu}_e) &= -\frac{G_F}{\sqrt{2}}\, V_{ud}\, \sqrt{4m_p m_n} \\
&\times\Big\{ g_S[\bar{u}_e(\vec{k}_e, \sigma_e)\, (1 - \gamma^5) v_{\tilde{\nu}_e}(\vec{k}_{\tilde{k}_e}, +\frac{1}{2})][\varphi^\dagger_p\varphi_n] \\
&+ g_T[\bar{u}_e(\vec{k}_e, \sigma_e)\vec{\alpha}\, (1 - \gamma^5) v_{\tilde{\nu}_e}(\vec{k}_{\tilde{\nu}_e}, +\frac{1}{2})][\varphi^\dagger_p\vec{\sigma}\,\varphi_n]\Big\},
\end{aligned}
\qquad (16)
$$

where $\vec{\alpha} = \gamma^0\vec{\gamma}$ is the Dirac matrix.

The total amplitude of the continuum-state β^-–decay of the neutron, containing the contributions of $V - A$, S and T interactions, is

$$
\begin{aligned}
M(n \to p + e^- + \tilde{\nu}_e) &= -\frac{G_F}{\sqrt{2}}\, V_{ud}\, \sqrt{4m_p m_n} \\
&\times\Big\{[\bar{u}_e(\vec{k}_e, \sigma_e)\, (\gamma^0 + g_S)\, (1 - \gamma^5) v_{\tilde{\nu}_e}(\vec{k}_{\tilde{k}_e}, +\frac{1}{2})] \\
&\times [\varphi^\dagger_p\varphi_n] \\
&+ [\bar{u}_e(\vec{k}_e, \sigma_e)(g_A\gamma^0 + g_T)\, \vec{\alpha}\, (1 - \gamma^5) v_{\tilde{\nu}_e}(\vec{k}_{\tilde{\nu}_e}, +\frac{1}{2})] \\
&\cdot [\varphi^\dagger_p\vec{\sigma}\,\varphi_n]\Big\}.
\end{aligned}
\qquad (17)
$$

The theoretical value of the continuum-state β^-–decay rate of the neutron, accounting for the contributions of scalar and tensor weak interactions, is

$$
\begin{aligned}
\tilde{\lambda}_{\beta^-_c} &= \frac{G^2_F |V_{ud}|^2}{2\pi^3} \\
&\times \Big\{((1 + 3g^2_A) + (g^2_S + 3g^2_T))\, f^{(\gamma)}(Q_{\beta^-_c}, Z = 1) \\
&+ 2(g_S + 3g_A g_T)\, \tilde{f}^{(\gamma)}(Q_{\beta^-_c}, Z = 1)\Big\},
\end{aligned}
\qquad (18)
$$

where $\tilde{f}(Q_{\beta^-_c}, Z = 1)$ is the Fermi integral equal to

$$\tilde{f}(Q_{\beta^-_c}, Z = 1) = = \int^{Q_{\beta^-_c} + m_e}_{m_e} \frac{2\pi\alpha m_e E_e (Q_{\beta^-_c} + m_e - E_e)^2}{1 - e^{-2\pi\alpha E_e/\sqrt{E^2_e - m^2_e}}} \times \Big(1 + \frac{\alpha}{2\pi}\, g(E_e)\Big)\, dE_e = 0.0404\,\mathrm{MeV}^5, \qquad (19)$$

where we have taken into account the contribution of the radiative corrections [13]. The function $g(E_e)$, calculated in [13], is given in the Appendix.

Neglecting the contribution of quadratic values of the scalar and tensor couplings, the continuum-state β^-–decay rate of the neutron is

$$\tilde{\lambda}_{\beta^-_c} = \lambda_{\beta^-_c}\,(1 + b\,\Delta_F), \qquad (20)$$

where $\Delta_F = \tilde{f}^{(\gamma)}(Q_{\beta^-_c}, Z = 1)/f^{(\gamma)}(Q_{\beta^-_c}, Z = 1) = 0.6612$ and b is the Fierz term [3] (see Eqs.(30) - (32)) equal to

$$b = 2\,\frac{g_S + 3g_A g_T}{1 + 3g^2_A} = 0.0032(23). \qquad (21)$$

The numerical value of the Fierz term is obtained from the fit of the experimental value $\tau^{\rm exp}_{\beta^-_c} = 878.5(8)\,\mathrm{s}$ [2]. For the linear combination $g_S + 3g_A g_T$ of the scalar and tensor coupling constant we get

$$g_S + 3g_A g_T = 0.0094(70). \qquad (22)$$

The contribution of the scalar and tensor weak interactions changes the amplitude of the bound-state β^-–decay as follows

$$M(n \to \mathrm{H}^{(ns)} + \tilde{\nu}_e) = G_F V_{ud}\sqrt{2m_n 2E_{\mathrm{H}} 2E_{\tilde{\nu}_e}} \times \Big\{(1 + g_S)\,[\varphi^\dagger_e \chi_{\tilde{\nu}_e}][\varphi^\dagger_p \varphi_n] - (g_A + g_T) \times [\varphi^\dagger_e \vec{\sigma}\,\chi_{\tilde{\nu}_e}]\cdot[\varphi^\dagger_p \vec{\sigma}\,\varphi_n]\Big\}\,\psi^*_{(ns)_F}(0). \qquad (23)$$

The bound-state β^-–decay rate of the neutron is equal to

$$\tilde{\lambda}_{\beta^-_b} = ((1 + g_S)^2 + 3(g_A + g_T)^2)\,\zeta(3)\,G^2_F |V_{ud}|^2 \times \frac{\alpha^3 m^3_e}{\pi^2}\sqrt{(m_p + m_e)^2 + Q^2_{\beta^-_c}}\,\frac{Q^2_{\beta^-_c}}{m_n}. \qquad (24)$$

Neglecting the contribution of the quadratic coupling constants of the scalar and tensor weak interactions we get

$$\tilde{\lambda}_{\beta^-_b} = (1 + b)\,\lambda_{\beta^-_b} = \lambda_{\beta^-_b}. \qquad (25)$$

Thus, the ratio $\tilde{R}_{b/c} = \tilde{\lambda}_{\beta^-_b}/\tilde{\lambda}_{\beta^-_c}$ of the bound-state and continuum-state β^-–decay rates of the neutron is not changed $\tilde{R}_{b/c} = 3.92 \times 10^{-6}$.

HELICITY AMPLITUDES AND ANGULAR DISTRIBUTIONS OF BOUND-STATE β^-–DECAY RATES OF NEUTRON

If the axis of the antineutrino–spin quantisation is inclined relative to the axis of the neutron–spin quantisation with a polar angle ϑ, the wave function $\chi_{\tilde{\nu}_e}$ can be taken in the following form

$$\chi_{\tilde{\nu}_e} = \begin{pmatrix} -e^{-i\varphi}\sin\frac{\vartheta}{2} \\ \cos\frac{\vartheta}{2} \end{pmatrix}, \qquad (26)$$

where φ is an azimuthal angle. The contributions of different spinorial states to the helicity amplitudes of the bound-state β^-–decay as functions of the angles ϑ and φ are adduced in Table I.

σ_n	σ_p	σ_e	$\sigma_{\tilde{\nu}_e}$	f
$+\frac{1}{2}$	$+\frac{1}{2}$	$-\frac{1}{2}$	$+\frac{1}{2}$	$(1 + g_S + g_A + g_T)\,\cos\frac{\vartheta}{2}$
$+\frac{1}{2}$	$+\frac{1}{2}$	$+\frac{1}{2}$	$+\frac{1}{2}$	$-(1 + g_S - g_A - g_T)\,e^{-i\varphi}\sin\frac{\vartheta}{2}$
$+\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$+\frac{1}{2}$	0
$+\frac{1}{2}$	$-\frac{1}{2}$	$+\frac{1}{2}$	$+\frac{1}{2}$	$-2(g_A + g_T)\,\cos\frac{\vartheta}{2}$
$-\frac{1}{2}$	$+\frac{1}{2}$	$-\frac{1}{2}$	$+\frac{1}{2}$	$2(g_A + g_T)\,e^{-i\varphi}\sin\frac{\vartheta}{2}$
$-\frac{1}{2}$	$+\frac{1}{2}$	$+\frac{1}{2}$	$+\frac{1}{2}$	0
$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$+\frac{1}{2}$	$(1 + g_S - g_A - g_T)\,\cos\frac{\vartheta}{2}$
$-\frac{1}{2}$	$-\frac{1}{2}$	$+\frac{1}{2}$	$+\frac{1}{2}$	$-(1 + g_S + g_A + g_T)\,e^{-i\varphi}\sin\frac{\vartheta}{2}$

TABLE I: The contributions of different spinorial states of the interacting particles to the amplitudes of the bound-state β^-–decay of the neutron and the antineutrino in the state with the wave function Eq.(26); f is defined by $f = (1 + g_S)[\varphi^\dagger_e \chi_{\tilde{\nu}_e}][\varphi^\dagger_p \varphi_n] - (g_A + g_T)[\varphi^\dagger_e \vec{\sigma}\,\chi_{\tilde{\nu}_e}]\cdot[\varphi^\dagger_p \vec{\sigma}\,\varphi_n]$.

Using the results in Table 1 we get the helicity amplitudes $M(n \to H_{FM_F} + \tilde{\nu}_e)_{\sigma_n, +\frac{1}{2}}$

$$M(n \to H_{00} + \tilde{\nu}_e)_{+\frac{1}{2},+\frac{1}{2}} = = M_0\frac{1 + 3g_A + g_S + 3g_T}{\sqrt{2}}\,\cos\frac{\vartheta}{2},$$
$$M(n \to H_{1,+1} + \tilde{\nu}_e)_{+\frac{1}{2},+\frac{1}{2}} = = -M_0(1 - g_A + g_S - g_T)e^{-i\varphi}\,\sin\frac{\vartheta}{2},$$
$$M(n \to H_{10} + \tilde{\nu}_e)_{+\frac{1}{2},+\frac{1}{2}} = = M_0\frac{1 - g_A + g_S - g_T}{\sqrt{2}}\,\cos\frac{\vartheta}{2},$$
$$M(n \to H_{1,-1} + \tilde{\nu}_e)_{+\frac{1}{2},+\frac{1}{2}} = 0,$$
$$M(n \to H_{00} + \tilde{\nu}_e)_{-\frac{1}{2},+\frac{1}{2}} = = M_0\frac{1 + 3g_A + g_S + 3g_T}{\sqrt{2}}\,e^{-i\varphi}\sin\frac{\vartheta}{2},$$
$$M(n \to H_{1,+1} + \tilde{\nu}_e)_{-\frac{1}{2},+\frac{1}{2}} = 0,$$

$$M(n\to H_{10}+\tilde{\nu}_e)_{-\frac{1}{2},+\frac{1}{2}} = = -M_0\frac{1-g_A+g_S-g_T}{\sqrt{2}}\,e^{-i\varphi}\sin\frac{\vartheta}{2},$$

$$M(n\to H_{1,-1}+\tilde{\nu}_e)_{-\frac{1}{2},+\frac{1}{2}} = = M_0(1-g_A+g_S-g_T)\,\cos\frac{\vartheta}{2}. \quad (27)$$

The angular distributions of the probabilities of the bound-state β^-–decays of the polarised neutron are equal to

$$4\pi\frac{dR^{(+)}_{F=0}}{d\Omega} = \frac{1}{8}\frac{(1+3g_A)^2}{1+3g^2_A}\,\frac{1}{1+b}\times\Big(1+2\,\frac{g_S+3g_T}{1+3g_A}\Big)\,(1+\cos\vartheta),$$

$$4\pi\frac{dR^{(-)}_{F=0}}{d\Omega} = \frac{1}{8}\frac{(1+3g_A)^2}{1+3g^2_A}\,\frac{1}{1+b}\times\Big(1+2\,\frac{g_S+3g_T}{1+3g_A}\Big)\,(1-\cos\vartheta),$$

$$4\pi\frac{dR^{(+)}_{F=1}}{d\Omega} = \frac{1}{8}\frac{(1-g_A)^2}{1+3g^2_A}\,\frac{1}{1+b}\times\Big(1+2\,\frac{g_S-g_T}{1-g_A}\Big)\,(3-\cos\vartheta),$$

$$4\pi\frac{dR^{(-)}_{F=1}}{d\Omega} = \frac{1}{8}\frac{(1-g_A)^2}{1+3g^2_A}\,\frac{1}{1+b}\times\Big(1+2\,\frac{g_S-g_T}{1-g_A}\Big)\,(3+\cos\vartheta), \quad (28)$$

where $R^{(\pm)}_F = (\lambda_{\beta^-_b})^{(\pm)}_F/\tilde{\lambda}_{\beta^-_b}$ and indices $(\pm)$ stand for the polarisations of the neutron.

For $g_S = g_T = 0$ these angular distributions of the decay probabilities agree well with those obtained by Song in [9]. Our polar angle ϑ is related to the polar angle θ in Song's paper as $\vartheta = \pi - \theta$.

The angular distributions, given in Eq.(28), can be used for the experimental search for the bound-state β^-–decay of the polarised neutron into hydrogen in the hyperfine state with $F = 1$. Since in the directions $\cos\vartheta = \mp 1$ the angular distributions of the probabilities of the production of hydrogen in the hyperfine state with $F = 0$ vanish, so for $\cos\vartheta = \mp 1$ one can detect only the bound-state β^-–decays of the neutron into hydrogen in the hyperfine state with $F = 1$.

The probabilities of decays into hydrogen in the certain hyperfine states are equal to

$$R_{F=0} = \frac{(\lambda_{\beta^-_b})_{F=0}}{\lambda_{\beta^-_b}} = \frac{1}{4}\,\frac{(1+3g_A)^2}{1+3g^2_A}\,\frac{1}{1+b}\times\Big(1+2\,\frac{g_S+3g_T}{1+3g_A}\Big) = 0.987(2)\,\Big(1+2\,\frac{g_S+3g_T}{1+3g_A}\Big),$$

$$R_{F=1} = \frac{(\lambda_{\beta^-_b})_{F=1}}{\lambda_{\beta^-_b}} = \frac{3}{4}\,\frac{(1-g_A)^2}{1+3g^2_A}\,\frac{1}{1+b}\times\Big(1+2\,\frac{g_S-g_T}{1-g_A}\Big) = 0.010(0)\,\Big(1+2\,\frac{g_S-g_T}{1-g_A}\Big), \quad (29)$$

where we have used the numerical values $g_A = 1.2750(9)$ and $b = 0.0032(23)$.

ELECTRON SPECTRUM OF CONTINUUM-STATE β^-–DECAY OF NEUTRON WITH CORRELATION COEFFICIENTS

The experimental measurement of the value of the axial coupling constant g_A can be carried out by measuring the electron energy spectrum and correlation coefficients [3]. The electron energy spectrum of the continuum-state β^-–decay of the neutron is equal to

$$\frac{d^5\lambda^{(\gamma)}_{\beta^-_c}}{dE_e d\Omega_e d\Omega_{\tilde{\nu}_e}} = (1+3g^2_A+g^2_S+3g^2_T)\times\frac{G^2_F|V_{ud}|^2}{16\pi^5}\,(Q_{\beta^-_c}+m_e-E_e)^2E_e\sqrt{E^2_e-m^2_e}\times F(E_e,Z=1)\,\Big(1+\frac{\alpha}{2\pi}\,g(E_e)\Big)\,\Big(1+a\,\frac{\vec{k}_e\cdot\vec{k}_{\tilde{\nu}_e}}{E_eE_{\tilde{\nu}_e}}+b\,\frac{m_e}{E_e}+A\,\frac{\vec{\xi}\cdot\vec{k}_e}{E_e}+B\,\frac{\vec{\xi}\cdot\vec{k}_{\tilde{\nu}_e}}{E_{\tilde{\nu}_e}}\Big), \quad (30)$$

where the coefficients a, A and B define the correlations between momenta of electron and antineutrino, neutron spin and electron momentum, and neutron spin and antineutrino momentum, respectively, $\vec{\xi}$ is the unit polarisation vector of the neutron. The Fierz term b [3] describes a deviation from the $V-A$ theory of weak interactions. The correlation coefficients are equal to

$$\begin{aligned} a &= \frac{1-g^2_A-g^2_S+g^2_T}{1+3g^2_A+g^2_S+3g^2_T},\\ b &= \frac{2(g_S+3g_Ag_T)}{1+3g^2_A+g^2_S+3g^2_T},\\ A &= -\,2\,\frac{g_A(g_A-1)+g_T(g_S-g_T)}{1+3g^2_A+g^2_S+3g^2_T},\\ B &= +\,2\,\frac{g_A(g_A+1)+g_T(g_S+g_T)}{1+3g^2_A+g^2_S+3g^2_T}\\ &\quad +2\,\frac{g_T+g_A(g_S+2g_T)}{1+3g^2_A+g^2_S+3g^2_T}\,\frac{m_e}{E_e}. \end{aligned} \quad (31)$$

Neglecting the contribution of g^2_S, g^2_T and g_Sg_T we get

$$a = \frac{1-g^2_A}{1+3g^2_A}\;,\; b = 2\,\frac{g_S+3g_Ag_T}{1+3g^2_A},$$

$$A = -2\,\frac{g_A(g_A-1))}{1+3g_A^2}\,,\; B = +2\,\frac{g_A(g_A+1)}{1+3g_A^2} + 2\,\frac{g_T + g_A(g_S+2g_T)}{1+3g_A^2}\,\frac{m_e}{E_e}. \qquad (32)$$

The coefficients a and A agree well with the results adduced in [3], whereas the coefficient B differs from that, given in [3], by the term inversely proportional to the energy of the electron and linear in scalar and tensor coupling constants. The value of the Fierz term $b = 0.0032(23)$ is given in Eq.(21).

NUMERICAL VALUE OF CKM MATRIX ELEMENT $|V_{ud}|$ IN $V-A$ THEORY OF WEAK INTERACTIONS

For the calculation of the lifetime of the neutron we have used the numerical value $|V_{ud}| = 0.97419(22)$ of the CKM matrix element, proposed in [4].

In this section we calculate the value of the CKM matrix element $|V_{ud}|$ in the $V-A$ theory of weak interactions, using our expression for the continuum-state β^-–decay rate of the neutron Eq.(11), calculated for the axial coupling constant $g_A = 1.2750(9)$ [3] and accounting for the radiative corrections, and the experimental values of the lifetimes of the neutron [1, 4]. From Eq.(11) with $f(Q_{\beta^-_c}, Z=1) \to f^{(\gamma)}(Q_{\beta^-_c}, Z=1)$ we get

$$|V_{ud}|^2 = \frac{4910.22}{\tau^{(\rm exp)}_{\beta^-_c}(1+3g_A^2)}. \qquad (33)$$

Using the experimental values of the lifetimes $\tau^{(\rm exp)}_{\beta^-_c} = 878.5(8)\,{\rm s}$ and $\tau^{(\rm exp)}_{\beta^-_c} = 885.7(8)\,{\rm s}$, measured in [1] and [2], respectively, we obtain

$$|V_{ud}| = \begin{cases} 0.9752(7)\,,\; \tau^{(\rm exp)}_{\beta^-_c} = 878.5(8)\,{\rm s} \\ 0.9713(7)\,,\; \tau^{(\rm exp)}_{\beta^-_c} = 885.7(8)\,{\rm s}. \end{cases} \qquad (34)$$

In Fig. 1 we show a dependence of the CKM matrix element on the values of the lifetime of the neutron and the axial coupling constant g_A. The yellow area shows that the value $|V_{ud}| = 0.9752(7)$, calculated for the lifetime $\tau^{(\rm exp)}_{\beta^-_c} = 878.5(8)\,{\rm s}$, agrees with both $|V_{ud}| = 0.97419(22)$ and $|V_{ud}| = 0.9738(4)$.

One can see that the value $|V_{ud}| = 0.9713(7)$, calculated for the lifetime $\tau^{(\rm exp)}_{\beta^-_c} = 885.7(8)\,{\rm s}$, is ruled out by the experimental value $|V_{ud}| = 0.9738(4)$, measured from the superallowed $0^+ \to 0^+$ nuclear β^-–decays, caused by pure Fermi transitions only [3, 19], and the unitarity of the CKM matrix elements giving $|V_{ud}| = 0.97419(22)$ [4].

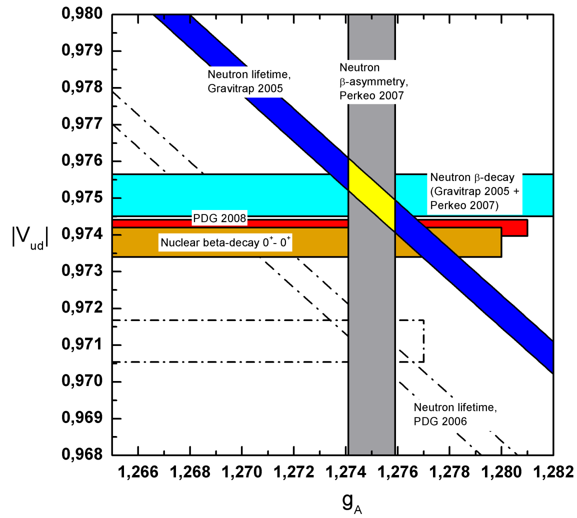

FIG. 1: The dependence of the CKM matrix element $|V_{ud}|$ on the values of the lifetime of the neutron and the axial coupling constant g_A.

CONCLUSIVE DISCUSSION

We have recalculated the continuum-state and bound-state β^-–decay rates of the neutron. Taking into account the contributions of weak and strong interactions for the lifetime of the neutron we get the value $\tau_{\beta^-_c} = 914.8(1.2)\,{\rm s}$, where the error $\pm 1.2\,{\rm s}$ is caused by the experimental error of the axial coupling constant $g_A = 1.2750(9)$ and the CKM matrix element $|V_{ud}| = 0.97419(22)$ [4]. Including the radiative corrections [13, 14], the theoretical value of the lifetime of the neutron changes to $\tau^{(\gamma)}_{\beta^-_c} = 880.4(1.1)\,{\rm s}$. It agrees well the experimental value $\tau^{(\rm exp)}_{\beta^-_c} = 878.5(8)\,{\rm s}$ [1].

We would like to accentuate that the radiative corrections are universal and make up about 3.9 %. The theoretical value of the radiative corrections, calculated in this paper

$$R_{RC} = \frac{f^{(\gamma)}(Q_{\beta^-_c}, Z=1)}{f(Q_{\beta^-_c}, Z=1)} = 1.03912, \qquad (35)$$

agrees well with the value $R_{RC} = 1.03886(39)$, given in [3].

The agreement of the theoretical value of the lifetime of the neutron $\tau_{\beta^-_c} = 880.4(1.1)\,{\rm s}$ with the experimental value $\tau^{(\rm exp)}_{\beta^-_c} = 878.5(8)\,{\rm s}$, measured in [1], is fully due to the axial coupling constant $g_A = 1.2750(9)$ and the CKM matrix element $|V_{ud}| = 0.97419(22)$ [4].

Using our expression (11) for the continuum-state β^-–decay rate with the Fermi integral, accounting for the contribution of radiative correc-

tions, the axial coupling constant $g_A = 1.2750(9)$ and the experimental lifetimes of the neutron $\tau^{(\rm exp)}_{\beta^-_c} = 878.5(8)\,{\rm s}$ [1] and $\tau^{(\rm exp)}_{\beta^-_c} = 885.7(8)\,{\rm s}$ [4] we got the values of the CKM matrix element $|V_{ud}| = 0.9752(7)$ and $|V_{ud}| = 0.9713(7)$, respectively.

It is seen that $|V_{ud}| = 0.9713(7)$ is ruled out by the values $|V_{ud}| = 0.9738(4)$ and $|V_{ud}| = 0.97419(22)$, defined from the superallowed $0^+ \to 0^+$ nuclear β^-–decays [3, 19] and the unitarity condition for the CKM matrix elements [4], respectively. This implies that the nature singles out the lifetime of the neutron $\tau^{(\rm exp)}_{\beta^-_c} = 878.5(8)\,{\rm s}$ [1]. Of course, this assertion should be confirmed by experimental data in other terrestrial laboratories. Some hints of the validity of this assertion can be found also in cosmology [25, 26].

For the axial coupling constant $g_A = 1.2750(9)$ the correlation coefficients are equal to

$$
\begin{aligned}
&a^{(\rm th)} = -0.1065(3)\ ,\ a^{(\rm exp)} = -0.103(4),\\
&B^{(\rm th)} = +0.9871(4) + 2\,\frac{g_T + g_A(g_S + 2g_T)}{1 + 3g^2_A}\,\frac{m_e}{E_e},\\
&B^{(\rm exp)} = +0.9821(40),\\
&C^{((\rm th)} = -0.2385(1)\ ,\ C^{(\rm exp)} = -0.2377(26), \qquad (36)
\end{aligned}
$$

where the coefficient $B^{(\rm exp)} = +0.9821(40)$ has been measured in [27, 28], $C = -0.27484\,(A + B)$ is the proton asymmetry, measured in [29].

We remind that the value $g_A = 1.2750(9)$ of the axial coupling constant has been calculated from the fit of the experimental value of the neutron spin–electron correlation coefficient $A^{(\rm exp)} = -\,0.11933(34)$, which has been obtained in [3] as an averaged value over PERKEO II measurements [30, 31].

The deviation of the theoretical value of the lifetime of the free neutron $\tau^{(\rm th)}_{\beta^-_c} = 880.1(1.1)\,{\rm s}$ from the experimental one $\tau^{\rm exp}_{\beta^-_c} = 878.5(8)\,{\rm s}$ [1] allows to take into the contributions of scalar and tensor weak interactions, which can be added to the standard $V - A$ baryon–lepton weak interactions with coupling constants g_S and g_T, respectively. From the fit of the experimental value of the lifetime of the neutron $\tau^{\rm exp}_{\beta^-_c} = 878.5(8)\,{\rm s}$ [1] we have found $g_S + 3g_Ag_T = 0.0094(70)$, caused by the value of the Fierz term $b = 0.0032(23)$ Eq.(21).

Since standard $V - A$ weak interactions describe well the experimental data on the coefficient of the neutron spin–antineutrino momentum correlation, we set zero the contribution of the energy–dependent term in the coefficient B. This gives $g_T + g_A(g_S + 2g_T) = 0$. Solving this equation together with the Fierz term Eq.(21) we estimate the scalar and tensor coupling constants

$$
\begin{aligned}
g_S &= +\,\frac{b}{2}\,\frac{(1 + 2g_A)(1 + 3g^2_A)}{1 + 2g_A - 3g^2_A} = -\,0.0251(181),\\
g_T &= -\,\frac{b}{2}\,\frac{g_A(1 + 3g^2_A)}{1 + 2g_A - 3g^2_A} = +\,0.0090(65) \qquad (37)
\end{aligned}
$$

The deviations from these values can be obtained experimentally by measuring the neutron spin–antineutrino momentum correlation and the bound-state β^-–decay rates of the neutron into hydrogen in certain hyperfine states. As we have shown the measurement of the angular distributions of the probabilities of the bound-state β^-–decay of the polarised neutron into hydrogen in the hyperfine states with $F = 1$ can be carried out at $\cos\vartheta = \pm 1$.

Our angular distributions for the probabilities of the bound-state β^-–decay rates of the neutrino into hydrogen in the certain hyperfine state agree at $g_S = g_T = 0$ with those obtained by Song [9].

APPENDIX A: RADIATIVE CORRECTIONS TO CONTINUUM-STATE β^-–DECAY RATE OF NEUTRON

Below we calculate the radiative corrections to the continuum-state β^-–decay rate following the results obtained in [13, 14]. Following [13] we determine the continuum-state β^-–decay rate with radiative corrections as follows

$$
\lambda^{(\gamma)}_{\beta^-_c} = (1 + 3g^2_A)\,\frac{G^2_F|V_{ud}|^2}{2\pi^3}\,f^{(\gamma)}(Q_{\beta^-_c}, Z = 1), \qquad \text{(A-1)}
$$

where the Fermi integral $f^{(\gamma)}(Q_{\beta^-_c}, Z = 1)$ is given by

$$
\begin{aligned}
&f^{(\gamma)}(Q_{\beta^-_c}, Z = 1) =\\
&= \int^{Q_{\beta^-_c} + m_e}_{m_e} \frac{2\pi\alpha E^2_e(Q_{\beta^-_c} + m_e - E_e)^2}{1 - e^{-\,2\pi\alpha E_e/\sqrt{E^2_e - m^2_e}}}\\
&\times \Big(1 + \frac{\alpha}{2\pi}\,g(E_e)\Big)\,dE_e = 0.0611\,{\rm MeV}^5. \qquad \text{(A-2)}
\end{aligned}
$$

The function $g(E)$, calculated in [13, 14], is

$$
\begin{aligned}
&g(E_e) = 3\,\Big[\ell n\Big(\frac{m_p}{m_e}\Big) - \frac{1}{4}\Big] + 4\,\Big[\frac{E}{2\sqrt{E^2_e - m^2_e}}\\
&\times \ell n\Big(\frac{E_e + \sqrt{E^2 - m^2_e}}{E - \sqrt{E^2 - m^2_e}}\Big) - 1\Big]\Big[\frac{Q_{\beta^-_c} + m_e - E_e}{3E_e}\\
&-\frac{3}{2} + \ell n\Big(\frac{2(Q_{\beta^-_c} + m_e - E_e)}{m_e}\Big)\Big] + \frac{4E_e}{\sqrt{E^2_e - m^2_e}}\\
&\times F\Big(\frac{2\sqrt{E^2_e - m^2_e}}{E_e + \sqrt{E^2_e - m^2_e}}\Big) + \frac{E_e}{2\sqrt{E^2_e - m^2_e}}
\end{aligned}
$$

$$\times \ell n\Big(\frac{E_e + \sqrt{E^2_e - m^2_e}}{E_e - \sqrt{E^2_e - m^2_e}}\Big)\Big[2\Big(1 + \frac{E^2_e - m^2_e}{E^2_e}\Big) + \frac{(Q_{\beta^-_c} + m_e - E_e)^2}{6E^2_e} - 2\,\ell n\Big(\frac{E_e + \sqrt{E^2_e - m^2_e}}{E_e - \sqrt{E^2_e - m^2_e}}\Big)\Big] + \Big[3\ell n\Big(\frac{m_W}{m_p}\Big) + \ell n\Big(\frac{m_W}{m_{a_1}}\Big) + 4\ell n\Big(\frac{m_Z}{m_W}\Big) + \frac{9}{4}\Big]. \tag{A-3}$$

The numerical value of the Fermi integral is calculated for $m_W = 80.4\,\mathrm{GeV}$ and $m_Z = 90.2\,\mathrm{GeV}$, the masses of the W and Z bosons of the standard electroweak theory by Weinberg–Salam [4], and $m_{a_1} = 1.2\,\mathrm{GeV}$, the mass of the axial meson [4, 13]. The Spence function $F(x)$ is defined by

$$F(x) = \int^x_0 \frac{\ell n(1-t)}{t}\,dt. \tag{A-4}$$

Following [13] we have neglected the contributions of electromagnetic corrections of order of $O(\alpha^2)$ and higher as well as the contributions of the finite radius of the proton, which is of order of $r_p \simeq 0.875(7)\,\mathrm{fm}$ [4]. This approximation can be justified by using the results obtained in [14]. For $\tilde{f}^{(\gamma)}(Q_{\beta^-_c}, Z = 1)$ we get $\tilde{f}^{(\gamma)}(Q_{\beta^-_c}, Z = 1) = 0.0404\,\mathrm{MeV}^5$.

The continuum-state β^-–decay rate of the neutron, accounting for the radiative corrections, is $\lambda^{(\gamma)}_{\beta^-_c} = 1.1359(14) \times 10^{-3}\,\mathrm{s}^{-1}$. The theoretical value of the lifetime of the neutron equal to $\tau^{(\gamma)}_{\beta^-_c} = 880.4(1.1)\,\mathrm{s}$ agrees well the experimental one $\tau^{(\exp)}_{\beta^-_c} = 878.5(8)\,\mathrm{s}$ by Serebrov *et al.* [1]. The error margins $\pm 1.1\,\mathrm{s}$ are fully determined by the experimental error margins of the axial coupling constant $g_A = 1.2750(9)$ [3] and the CKM matrix element $|V_{ud}| = 0.97419(22)$ [4].

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